Effects of Thinning in Black Spruce Feathermoss Forests on Duff Moisture Content and Predicted Fire Behavior

By
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Hobo Weather Station located at Delta control plot.

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Submitted in fulfillment of the senior thesis requirements of the Department of Environmental Science at Allegheny College and approved by the senior thesis committee.

Dr. Richard Bowden	**Date**	**Dr. Terrance Bensel**	**Date**

Pledge

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Abstract

Fire is a critical disturbance that maintains boreal ecosystems. Black spruce (*Picea mariana*) trees are very flammable and have high crowning potential. Stands are thinned to create shaded fuelbreaks used to slow the rated of fire spread (Agee et al. 2000) and protect towns and villages. However, thinning can potentially alter the moisture content of ground fuels (moss and duff layers) and therefore alter predicted fire behavior. Duff samples were taken from thinned (3 m x 3 m spacing and pruned up to 1.2 m) and control (unthinned) sites in Delta, Tanacross, and Toghotthele land located in Interior Alaska. Moisture content in live moss, dead moss, and upper duff fuel layers was measured with Campbell Scientific DMM-600. Overall, moisture content in thinned plots was statistically drier than control plots ($p = <.0001$). The measured Fire Weather Index used to predict fire characteristics were higher in thinned areas indicating increased fire behavior. Remote Automated Weather Stations overestimated the Duff Moisture Code by an average 70.8, while the Fire Weather Index was overestimated by 2.4. Thinned tree stands have drier moisture dynamics that are not consistently illustrated by the current fire prediction models and could critically impact management decisions.

Introduction

The boreal forest is one of the largest circumpolar ecosystems, inhabiting a belt more than 1000 km wide in some areas and covering over 12 x 10^6 km^2 of the globe (Larsen, 1980; Payette, 1992). Forest fires are one of the major disturbances that strongly influence species composition, community structure, and forest function (Agee, 2002; Pastor and Mladenoff, 1992). Fire cycles can range from 29 - 400 years in the interior Alaska taiga (Dyrness et al. 1986) creating gaps in the canopy, which control vegetation development (Payette, 1992). The mosaic arrangement of forests in this region is dependent on fire to facilitate succession (Viereck et al. 1986) and determine the distribution of the dominant tree species (Dyrness et al. 1986).

Interior Alaska has limited diversity in vegetation type with only six dominant tree species (Viereck et al. 1986). Black spruce (*Picea mariana*) occupies 44% of this region (Viereck et al. 1986) and is the most prevalent forest type in the taiga community (Rupp et al, 2002). Black spruce stands are generally located on poorly drained sites, due to underlying permafrost, and on a moderate to wet moisture gradient (Larsen, 1980). These stands generally have a one-layered closed canopy with low growing shrubs, and a thick ground cover of mosses, primarily feather mosses (*Hylocomium splendens* and *Pleurozium schreberi*), and lichens with other low herbaceous plants, such as bluejoint reedgrass (*Calamagrostis Canadensis*) and fireweed (*Epilobium angustifolium*) (1980).

The problem fuel type in interior Alaska is black spruce (*Picea mariana*). A study conducted by Rupp et al (2002) suggests that adding black spruce to a vegetation dynamic model significantly shortened the fire cycle and increased the magnitude of the fire. Forty to sixty year old black spruce stands can become very dense with up to 4,000 – 6,000 stems/ha (Viereck et al.

1986). Dead branches are typically covered with lichens and extend to the ground surface, making it a very hazardous ladder fuel (Johnson, 1992). The low-growing branches increase the potential for surface fires to escalate into dangerous crown fires. Spruce litter is also very flammable and decomposes very slowly, inducing shorter fire return intervals of 50 – 70 years (Pastor and Mladenoff, 1992; Viereck, 1986). Lichen ground cover responds very quickly to changes in temperature and humidity making it extremely flammable and contributes to common lightning-ignited fires (Payette, 1992).

Low temperatures and slow decomposition rates create a thick organic layer, composed of feathermoss material, which can accumulate up to 50 cm in depth (Viereck, 1986). This ground fuel can be divided into 4 distinct combustible layers. The moss layer is a living fuel and has two components - the green live stems and the brown stems no longer photosynthesizing under reduced light conditions (Dryness and Norum, 1983). The third and fourth layers are decomposing organic material, or duff, and lie on top of the mineral soil. A layer of fungal mycelia separates the two layers of upper and lower duff (1983). Some of the moss structure is still identifiable above the fungal layer while below the layer is highly decomposed and very compact, prohibiting heat transfer from the surface and retaining moisture (1983).

The feathermoss forest floor plays an important and complex role in forest fire dynamics in boreal ecosystems. The moss layers serve as fine fuels, which contribute to surface ignition and fire severity (the degree of ecological impact on the vegetative community) (Barney et al. 1981; Payette, 1992). The deeper organic duff layers contribute to the overall fire intensity (the energy released during combustion) (Payette, 1992) and duration by providing a sustainable fuel source and allowing the fire to burn to mineral soil (Lawson et al, 1997).

Duff consumption is critical to boreal ecosystem functions, producing most of the energy that supports fires (Lawson et al, 1992). Moisture content of the organic layers is linked directly to the amount of material consumed (Dryness and Norum, 1983). As moisture content decreases, the level of consumption increases. Schimmel and Granstrom (1996) found that the depth of consumption is more critical to vegetation regeneration than fire front intensity and determines successional processes. Overall, the duff moisture content plays a very large role in determining fire behavior characteristics (such as intensity, severity, and consumption) and controls the ability to ignite and sustain combustion (Lawson et al. 1997).

Low fuel moistures are common throughout the summer months (May to August) throughout interior Alaska and can produce extreme fire conditions. This can be very dangerous when black spruce feathermoss communities surround cities and villages. Alaska has seen a dramatic increase in settlement in the Wildland Urban Interface since the 1970's where almost 80% of the current population lives in a high-risk area dominated by black spruce feathermoss (Ott et al. 2001). Growth in population density has increased human interaction with forested areas and lead to more frequent anthropogenic ignitions (Guyette et al. 2002). More infrastructures have developed in remote areas increasing the threat of wildfire.

The cost of structure and settlement protection has continued to increase putting more stress on fire management officials. To help combat this problem, several different management techniques have been utilized across the state to create defensible spaces, areas free of vegetation, for protection. Shaded fuelbreaks are preferred in forested areas surrounding local communities because of aesthetic desirability. Shaded fuelbreaks are constructed by thinning the tree stand, increasing the height to the live crown on the remaining trees, and modifying ground fuels (Agee et al, 2000). They are designed to enhance suppression efforts (2000) and reduce crown fire potential and intensities (Agee, 2002).

The effectiveness of this treatment is highly debatable across the United States. Shaded fuelbreaks have been used successfully in the western United States (3 million acres were scheduled to be treated in 2003) but the forest structure and fire regime is very different at northern latitudes (National Interagency Fire Center, 2003). Thinning can potentially have undesirable effects on duff moisture and reduce the success of structure protection. Opening the canopy can conceivably increase the ground temperature and surface winds resulting in drier fuels but few studies been conducted to confirm these theories in boreal ecosystems (Theisen, 2003). Studies conducted in Pacific Northwest forests have shown very different results than what might be expected in interior Alaska. Thinning allowed understory vegetation to green-up, which increased foliar moisture and dampened potential surface fire behavior (Agee et al. 2001). Another study looked at the influence of thinning and burning treatments on ponderosa pines and found that soil water content was the highest in thinned stands (Feeney et al. 1998).

The ability to estimate fuel moisture is essential for fire managers to predict fire behavior and effectively manage forest fires. Fire managers in Alaska use a subset of the Canadian Forest Fire Danger Rating System (CFFDRS) called the Fire Weather Index (FWI) to evaluate various factors that affect ignitability and probable fire behavior for proper fire management (Stocks et al. 1989). The FWI is a numerical rating system that is comprised of five elements that address fuel moisture and weather conditions (Appendix A). The danger-rating indices correspond to specific potential fire behavior characteristics, such as ignition probability, rate of spread, burn severity, and fire line intensity, and are essential to several significant fire related applications (De Groot, 1987).

This project is designed to determine the effects of thinning on duff moisture content in black spruce feathermoss communities. Additionally, I will examine the relationship between moisture content and predicted fire behavior.

Methods

Study Sites

Moisture samples were collected from three sites in central to western interior Alaska. Site one was located on the Delta Junction State Bison Range (63^0 44' N, 144^0 42' W) 20 km southeast of Delta Junction, Alaska. Site two was on property owned by the Toghotthele Corporation (approximately 64^0 34' N, 149^0 5' W), 72 km southwest of Fairbanks, Alaska. The final sampling site was located in the Native village of Tanacross, Alaska (63^0 22' N, 143^0 22' W), 19 km northwest of Tok (Appendix B). Sites exist along an approximately 260 km gradient. The slope at each site is approximately zero.

Climatic conditions throughout interior Alaska exhibit large diurnal and annual variations in temperature but generally have brief mild summers, averaging a daily temperature of 17^0C in July, with long harsh winters averaging $^-24^0$C in January (Larsen 1980, Shugart et al. 1992, Van Cleve, 1986). Summer temperatures as high as 38^0C have been reported in this region (Larsen, 1980). Central Alaska is generally distinguished by low annual precipitation due to interception by the Alaska Range (Van Cleve, 1986). Approximate average annual rainfall for the Delta, Toghotthele, and Tanacross sites are 30.3 cm, 23.4 cm, and 21.8 cm respectively (Alaska Climate Research Center, 2004). Approximately 60% of the annual precipitation occurs from May through August.

Permafrost is discontinuous throughout this section of Alaska (Larsen, 1980) but was present at all of the sampling sites with active layer depths ranging from 25 cm in Toghotthele to 80 cm in Tanacross (active layer may be deeper that estimated in Tanacross due to soil compaction). The active layer depth at Toghotthele was very shallow with permafrost still incorporated in lower organic layers. Gelisols, soils that contain permafrost within 2 m of the surface causing thick build up organic material and poor drainage, are predominant at the Delta and Toghotthele sites (1980). Tanacross is situated on the previous Tanana River flood plain with silty, compacted, moderately-drained soils.

The three sites are dominated by a black spruce (*Picea mariana*) overstory with mixed white spruce (*Picea glauca*) in Tanacross. The low shrub layer is primarily composed of labrador tea (*Ledum groenlandicum*) and lowbush cranberry (*Vaccinium vitis-idaea*). Feather mosses (*Pleurozium schreberi* and *Hylocomium splendens*) predominate the surface layer. The depth of the organic layer (surface to upper duff layer) varied between sites ranging from 7 cm in Tanacross to 29 cm in Delta.

Toghotthele and Delta sampling areas were established within Joint Fire Science Boreal Forest Fuel Demonstration Project Sites (constructed in 2001 and 2002) designed to compare the costs and benefits and determine the ecological effects of different shaded fuelbreak designs. Five one-acre plots were constructed with four distinct thinning treatments; 2.4 m (8 feet) spacing between trees (approximately 680 trees/acre), 2.4 m spacing and limbed to 1.2 m, 3 m (10 feet) spacing (approximately 435 trees/acre), 3 m spacing and limbed, and control. Hobo weather stations are located in the control and 3 m pruned treatment at the Delta site.

The Tanacross sampling site was part of a hazardous fuels reduction project in 2001 where 27 hectares surrounding the village were thinned to an approximate 3 m interval and pruned slightly higher than 1.2 m, reducing the tree density from 884 trees/acre to 225 trees/acre. Remote Automated Weather Stations (RAWS) were set up in one of the treated areas and one of the adjacent control areas to report daily weather and Canadian Fire Weather Index ratings.

Data Collection

Duff moisture was sampled from July 24th to July 30th, 2003. Moisture data were collected from the most extreme treatment of 3 m tree spacing and pruned to 1.2 m at the Delta and Toghotthele sites to ensure that all three sites had a similar thinning interval and pruning height. Each of the sampling sites (Delta, Toghotthele, and Tanacross) contained a treatment plot and a control plot. Six duff plugs were removed from each treatment and each control plot at all three sites. The moisture content of the live moss, dead moss, and upper duff layers from each plug was measured.

Duff plugs were taken randomly at Delta and Toghotthele but followed certain parameters. These parameters include: minimizing edge effects by avoiding areas within 5 m of the perimeter, sampling outside of the 5 subplots with the exception of the center plot, and avoiding transect lines to reduce impacts to the ongoing fuel demonstration study. The Tanacross site is split up into three sections where the Alaska Fire Service is also collecting data. Two duff samples were collected in each of the three treated sections along with two samples from each of the three adjacent control areas. Samples were gathered randomly but transect lines were avoided. General physical characteristics that best exhibit the natural features of the area were also considered in selecting a location to sample. Areas that were not feather moss, trampled by human, bison trails, at the base of a tree, and extreme hummocks and dips were avoided to get the most representative samples.

Destructive sampling techniques were used to remove the duff plug from the forest floor. A 10 cm x 10 cm square of moss was cut with a compass saw down to mineral soil or lower duff layer if mineral soil could not be obtained. The duff plugs were carefully extracted to prevent compaction, which alters the moisture gradient within the sample. Once removed, the live moss, dead moss, and upper duff fuel layers were separated. The lower duff layer was not included in this experiment because of highly variable moisture content and minimal relevance in predicting fire behavior. The live moss layer consists of the green section of the feathermoss. The dead moss layer is brown in color but has not begun to decompose. The upper duff fuel layer consists of partially decomposed, dark brown material but stem fragments are still visible (Appendix C.1). The bulk density of each layer increases with decomposition.

Volumetric water content was measured in the field with the Campbell Scientific DMM-600 Duff Moisture Meter. This device, based on time domain reflectometry, compresses the sample to determine the presence of water by using high frequency signals linked to circuits in the bottom of the sample chamber and a calibration equation for conversion to volumetric water content (Campbell Scientific, Inc., 2001). Each fuel layer was measured by chopping up a vertical section of the layer with clippers (for even compression) and inserted in the chamber of the DMM-600. The sampling technique was standardized by using only the upper 5 cm of each moss layer.

Data Analysis

Using StatView, a three-way analysis of variance (ANOVA) was conducted with variables including site, treatment, and fuel layer to show significant differences or interaction effects of moisture content between Delta, Toghotthele, and Tanacross; thinned and control samples; and live moss, dead moss, and upper duff. Fisher's Paired Least Significant Difference (PLSD) test was used to further distinguish which specific sites and fuel layers were significantly different. Multiple one-way ANOVA's were used to determine significant differences in moisture content in each fuel layer between the thinned and unthinned treatments.

The volumetric moisture content (the volume of water in a known amount of material) was converted to gravimetric moisture content (the ratio of the mass of water to the mass of material with no water) (Campbell Scientific, Inc., 2001). The DMM-600 was not calibrated to feathermoss bulk densities so conversion factors were derived using two duff plugs that were both oven dried and measured with the DMM-600 for gravimetric and volumetric moisture contents. The moisture samples were converted with the following equation:

$$\text{Estimated Grav MC} = \frac{\underline{(\text{Vol MC/bulk density})*(\text{Vol MC*cf})}}{\text{Vol MC}}$$

where Vol MC is the volumetric moisture content measured with the DMM-600, cf is the conversion factor that corresponds to the duff layer (live moss = 0.10, dead moss = 0.18, and upper duff = 0.27), and the Estimated Grav MC is the estimated percent gravimetric moisture content used in further calculations. Bulk densities for black spruce feathermoss (live moss = 0.014 Mg/m^3; dead moss = 0.023 Mg/m^3; upper duff = 0.044 Mg/m^3) were derived from Wilmore (2001).

The Duff Moisture Code (DMC) and the Drought Code (DC) (Appendix A) are calculated with the following equations:

$$\text{DMC} = \{[\ln(\text{MC})](-20.9)\}+149.6$$

$$\text{DC} = [\ln(488.4/\text{MC})]*267.9$$

where MC is the gravimetric moisture content (Lawson et. al. 1997). Dead moss moisture content is used to calculate the Duff Moisture Code and upper duff moisture content is used for the Drought Code. The Fine Fuel Moisture Code is not calculated directly from live moss moisture. All samples were split up by date so the most accurate weather data could be applied to the fire behavior prediction model. A paired t-test was used to determine significant differences between the thinned and control Duff Moisture Code and Drought Code.

The Fire Weather Index (FWI) was computed from several components: Fine Fuel Moisture Code reported by the nearest Remote Automated Weather Station; measured Duff Moisture Code (calculated from moisture samples); measured Drought Code (calculated from moisture samples); and Initial Spread Index (ISI) and Build Up Index (BUI) through the use of Tables for the Canadian Forest Fire Weather Index System (1987). Wind speed at 1400 hours, a component of the ISI, was determined by two Hobo weather stations within the control and thinned plots in Delta, RAWS Alaska Portable #4 and #5 within control and thinned plots in Tanacross, and the Nenana ASOS weather station, 16 km southwest of Toghotthele. Paired t-tests were also used to assess the association between control and thinned FWI ratings.

Remote Automated Weather Stations estimate the Fire Weather Index and all of the components based on empirically-derived formulas and weather measurements. RAWS estimates were compared to measured fuel codes using linear regression analysis and paired t-tests. Hobo weather stations do not calculate fuel codes so the Dry Creek RAWS (approximately 20 km northeast of Delta, was used to estimate control and thinned values. The Fairbanks Airport RAWS was the closest reporting station, 88 km northeast of Toghotthele site. Alaska Portable #4 and #5 were used for Tanacross treatment and control plots.

Additional Tanacross duff moisture sampling data was obtained from the United States Fish and Wildlife Service Tetlin National Wildlife Refuge. These data were used to supplement the moisture data collected in this experiment and show temporal changes in duff moisture and fuel codes in thinned and control areas.

Results

Moisture Content

A total of 108 duff moisture measurements were collected (Appendix D.1). The average percent volumetric moisture content ranged from 3.9 in thinned live moss to 22.7 in the control upper duff layer. A three-way ANOVA revealed extremely significant differences in percent moisture content (volumetric) within the sites (Delta, Tanacross, and Toghotthele); the treatment (thinned and control); and the fuel layer (live moss, dead moss, and upper duff (p = < .0001) (Table 1). Fisher's Paired Least Significant Difference (PLSD) showed that only dead moss and upper duff layers displayed no significance in percent moisture content (Table 2).

Table 1. Summary statistics for three-way ANOVA.

Variable	DF	Sum of Squares	Mean Square	F-Value	P-Value
Site	2	2478.1	1239.1	30.4	<.0001
Treatment	1	867.0	867.0	21.3	<.0001
Layer	2	1106.9	553.5	13.6	<.0001
Site*Treatment	2	640.5	320.3	7.9	0.0007
Site*Layer	4	507.1	126.8	3.1	0.019
Treatment*Layer	2	342.4	171.2	4.2	0.018
Site*Treatment*Layer	4	533.6	133.4	3.3	0.015

Table 2. Fisher's Paired Least Significant Difference

Feature	Variable	Mean Diff.	P-Value
Site	Delta, Tanacross	6.306	<.0001
	Delta, Toghotthele	-5.417	0.0005
	Tanacross, Toghotthele	-11.722	<.0001
Treatment	Thinned, Unthinned	-5.667	<.0001
Fuel Layer	Live Moss, Dead Moss	5.667	0.0003
	Live Moss, Upper Duff	-7.528	<.0001
	Dead Moss, Upper Duff	-1.861	0.2192

Overall, moisture content in thinned and control areas was significantly different in live moss (p = < 0.0001) and dead moss (p = 0.0007) layers in two of the three sites (Table 3). The thinned samples were consistently drier than the control with the exception of the upper duff in Delta (Figure 2a-c). Live moss and dead moss moisture content is drastically drier in thinned stands than control in Delta and Tanacross (Figure 2a and 2b). There is much less difference in moisture content between thinned and control plots in upper duff but is only statistically different in Tanacross.

Table 3. One-way ANOVA results for thinned and control fuel layers on percent volumetric moisture content.

	Live Moss		Dead Moss		Upper Duff	
Site	*F*	*P*	*F*	*P*	*F*	*P*
Delta	30.861	0.0002	18.417	0.0016	0.902	0.3646
Toghotthele	15.035	0.0031	9.421	0.011	0.955	0.3516
Tanacross	0.135	0.7208	0.462	0.5123	18.182	0.0017
Combined	39.508	< 0.0001	14.218	0.0007	0.314	0.5796

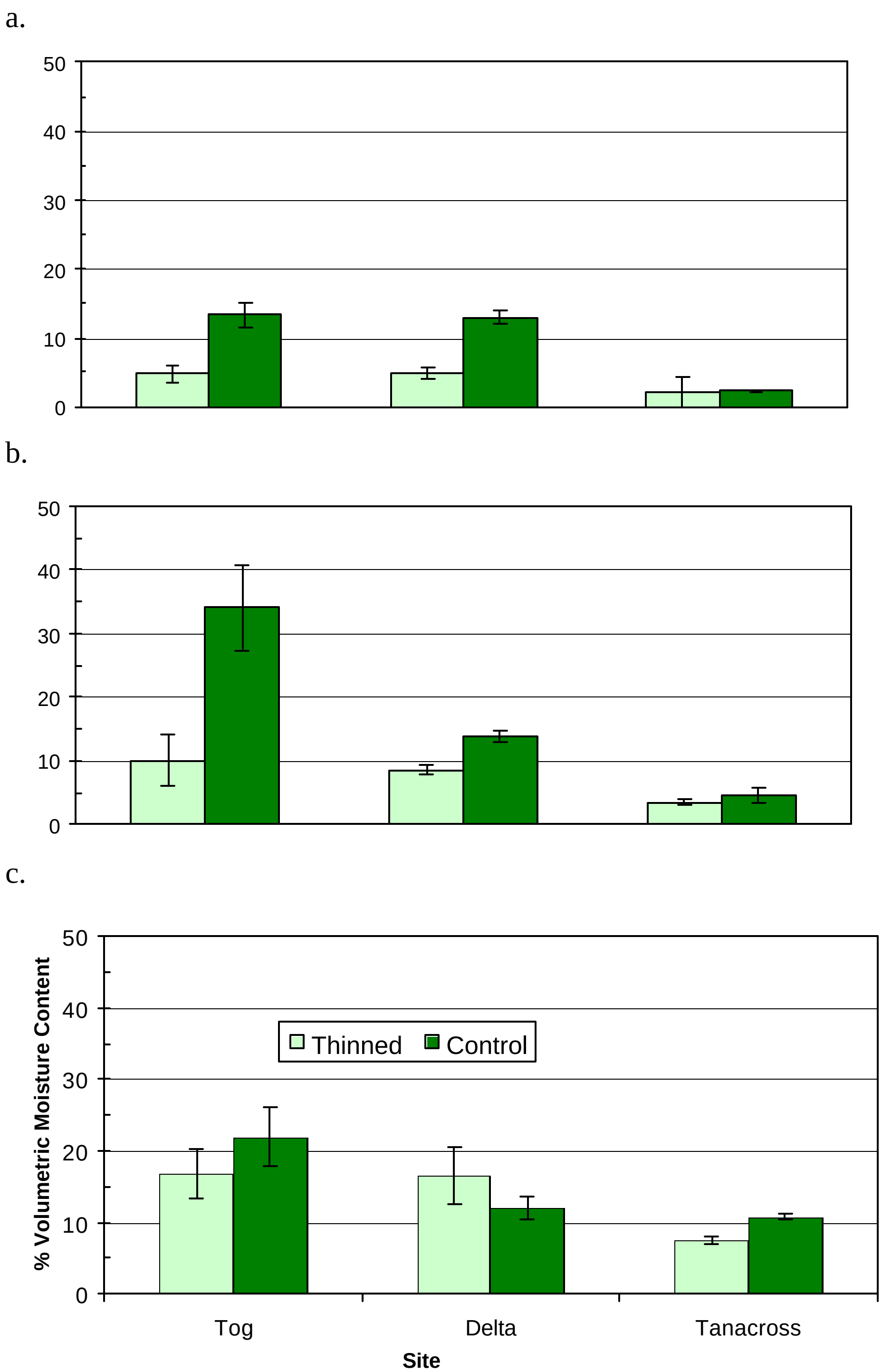


Figure 2. Thinned and control (unthinned) percent volumetric moisture content (mean +/- 1 SE; n = 6) by site for live moss (a), dead moss (b), and upper duff (c) fuel layers in black spruce feathermoss forest.

Fuel Moisture Codes

Fuel codes from this study were combined with Tetlin-Tanacross data (Appendix D.2 and D.3) to enhance the relationship between thinned and control values. Paired t-tests revealed that the thinned Duff Moisture Code values ($t = -3.300$; critical value = 2.179) and Fire Weather Index ratings ($t = 3.533$; critical value = 2.179) are significantly higher than the control by an average of 13.8 and 2.3, respectively. The Drought Code, which closely corresponds to the upper duff moisture content, is not significantly different ($t = 0.044$, critical value = 2.179). The measured values for the Duff Moisture Code, Drought Code, and Fire Weather Index in thinned plots were higher than control in 92%, 54%, and 85% of the samples respectively.

The Tetlin-Tanacross data combined with the two sample dates from this study display a more temporal picture of moisture dynamics throughout the season. Figures 3, 4, and 5 show changes in measured thinned and control Duff Moisture Code and Drought Code values along with Remote Automated Weather Station (RAWS) estimated values over a span of 77 days. RAWS estimated Fuel Moisture Code data were not reported for the first two sampling dates in the thinned treatment.

The Duff Moisture Code shows an overall drying effect throughout the summer (as values increase, moisture content decreases) (Figure 3). All Duff Moisture Code values were similar through May 21st and then began to diverge on through the last sample date. The measured treatment Duff Moisture Code was higher than the control, with the exception one sampling date, indicating that the thinned area is consistently drier. The RAWS began to overestimate the measured values on June 4th and continued to do so as fuel moistures decreased.

The Drought Code generally increased, indicating continual drying throughout the summer season (Figure 4). The margin between RAWS estimated values and measured Drought

Code values increased as the season progressed. The distinction between thinned and control Drought Code values is not as clear as the Duff Moisture Code.   Drier conditions in the upper duff indicate a less pronounced impact from thinning.

The Fire Weather Index was generally higher in the thinned than the control areas. The RAWS also overestimated the measured values throughout the season. Extremely low wind speeds on June 20th caused a depression in thinned and control Fire Weather Indices, which shows that wind speed is a very important element of the behavior prediction model.

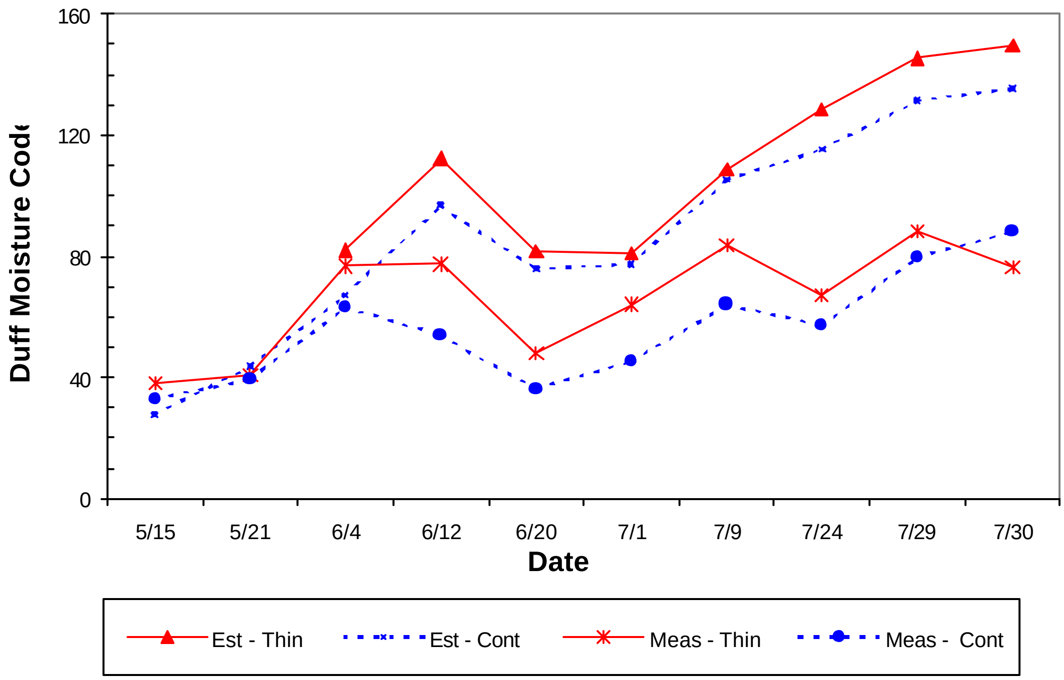


Figure 3. Duff Moisture Code Values for Tetlin – Tanacross and Tanacross data, where Est – Thin = RAWS estimate in thinned plots, Est - Cont = RAWS estimate in control plots; Meas – Thin = Measured in thinned plots, and Meas – Cont = Measured in control plots.

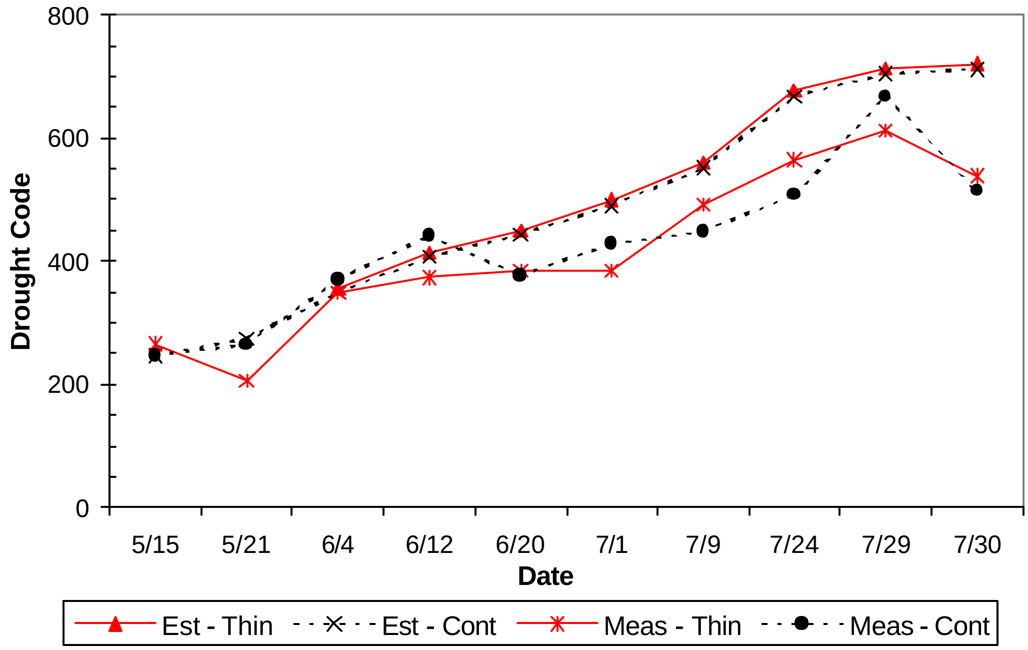


Figure 4. Drought Code for Tetlin – Tanacross and Tanacross data, where Est – Thin = RAWS estimate in thinned plots, Est - Cont = RAWS estimate in control plots; Meas – Thin = Measured in thinned plots, and Meas – Cont = Measured in control plots.

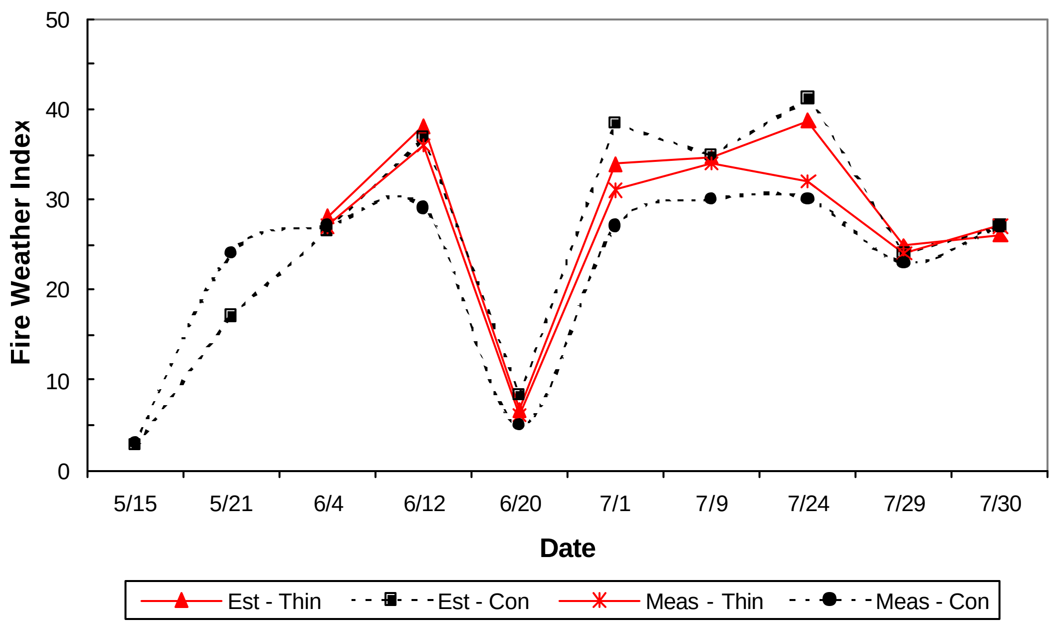
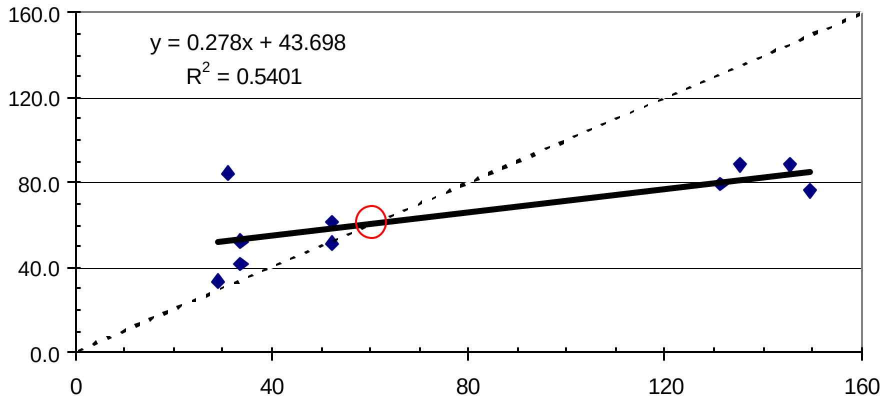


Figure 5. Fire Weather Index values for Tetlin – Tanacross and Tanacross data measure in this study, where Est – Thin = RAWS estimate in thinned plots, Est - Cont = RAWS estimate in control plots; Meas – Thin = Measured in thinned plots, and Meas – Cont = Measured in control plots.

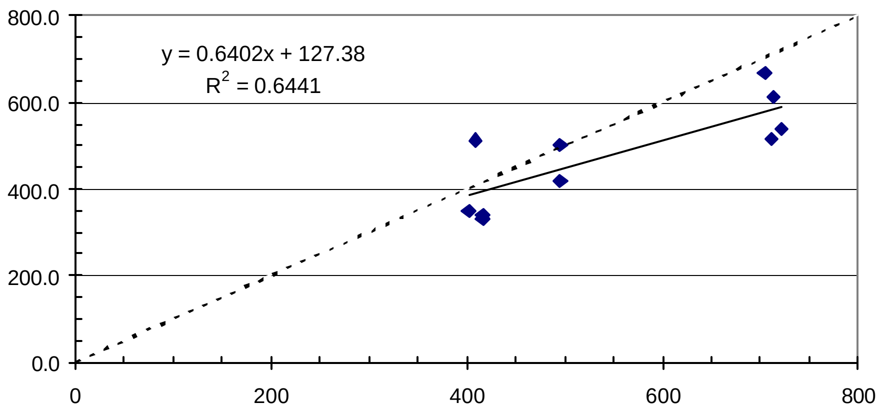
Remote Automated Weather Stations

Regression analysis of RAWS estimated and measured Duff Moisture Code, Drought Code, and Fire Weather Index displayed two different trends (Appendix D.4). The RAWS underestimated the Duff Moisture Code until approximately 60 and then overestimated the values by up to 73 points (Figure 6a). The Drought Code and Fire Weather Index show a similar trend with RAWS estimated values closest to measured at the lower values and then increasingly overestimated the ratings as moisture content decreased (Figures 6b and 6c). A paired t-test shows a significant difference between the RAWS estimated and measured Drought Code values ($p = 2.56$; critical value = 2.26) and Fire Weather Index ($p = 2.64$; critical values = 2.26).

a.



b.



c.

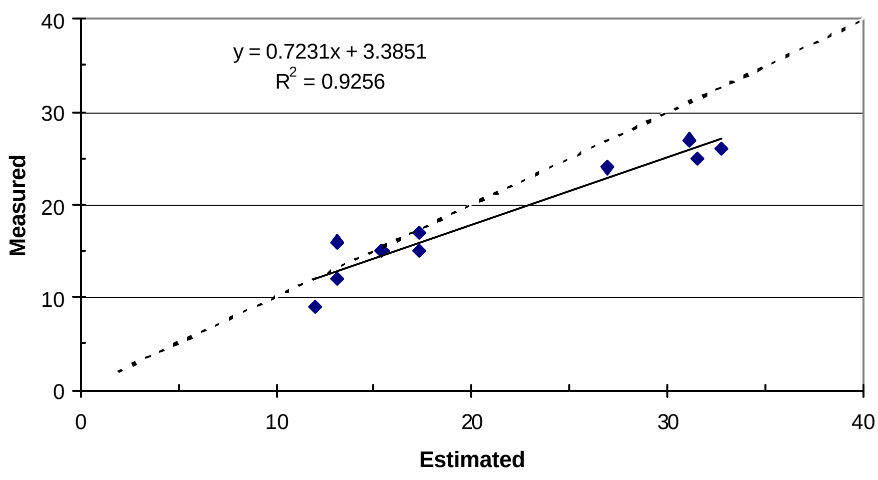


Figure 5. RAWS estimated values versus measured values for the Duff Moisture Code (a), Drought Code (b), and Fire Weather Index (c).

Discussion

Duff Moisture Content

Surface fuels in thinned black spruce stands are drier than in unthinned areas. The three-way ANOVA reflects an extreme difference in total moisture content between thinned and control plots (p = <0.0001). Even though Delta, Toghotthele, and Tanacross sites are statistically different from each other (Table 1), the thinning treatment still induced drier fuel conditions.

The live moss and dead moss in Delta and Toghotthele were significantly drier under an open canopy than closed (Table 3; Figures 2a-b). There are several possible factors that could contribute to drier conditions in Delta and Toghotthele. The open canopy allows more sunlight to reach the surface, drying out the fuels and increasing the ground temperature. Increased wind speeds also aid in the drying process. Wind damage to standing black spruce trees was noted in a thinned plot at the Delta site, indicating high gust wind speeds not experienced in the control areas (Appendix C.2). Long term increased ground temperatures could increase the depth to permafrost and allow moisture to drain farther down into the mineral soil instead of being held in the duff layers. Feathermoss does not thrive under drier, more exposed conditions. There is a noticeable difference in "greenness" or live ground fuels between the thinned and control plots in Delta (Appendix C.2 and C.3).

The upper duff was not significantly drier in Delta and Toghotthele (Table 3; Figures 2a-b). The upper duff has a much longer time lag (the time it takes the fuel to lose 2/3 of moisture content) of 53 days, compared to 2/3 of a day for live moss and 12 days for dead moss, and only responds to a 24-hour rainfall greater than 2.8 mm (De Groot, 1987). This layer is heavily insulated by the live and dead moss, which reduces thinning impacts. Delta and Toghotthele are generally more representative of black spruce feathermoss communities in interior Alaska therefore similar drying trends would be expected throughout this region.

Thinning in Tanacross showed the opposite effect on moisture content, with only a significant difference in upper duff. This region received 3.2 cm of rainfall in the previous 30 days, causing extremely dry conditions in the live and dead moss layers. The average depth of the organic layer in Tanacross was only 14 cm compared to 17 cm and 21 cm in Toghotthele and Delta, which allowed the upper fuel layers to dry faster. It is possible that the extremely dry conditions lowered the moisture content of the live and dead moss layers to such an extent that the effects of thinning were negligible (Appendix C.4). The above layers protected the upper duff layer but not enough to avoid enhanced drying conditions via thinning.

Predicted Fire Behavior

The behavior of forest fires is very dependent on the moisture of surface fuels in black spruce feathermoss communities. Moisture content controls ignition, continuity of combustion, fuel consumption, and overall fire intensity (Lawson, 1997). The Fuel Moisture Codes attempt to forecast how a fire might burn under certain moisture conditions. According to Agee et al. (1999), the combination of moisture data and behavior indices (in this case the Build Up and Initial Spread Index) can predict fire-line intensities needed to reach the critical level where crown fires are initiated.

The moisture content of the live moss layer is very important because it determines the ease of ignition. The combination of wind speed and live moss moisture indicates the rate of fire spread (represented in the Initial Spread Index). The live moss in Delta and Toghotthele was substantially drier in thinned stands almost dead in Tanacross. Thinned areas in Toghotthele and

Delta could have a higher ignition probability along with a faster rate of fire spread compared to the control. The conditions in Delta may be even more significant because of intermixed lichen cover. Lichens respond to changes in humidity and temperature extremely quickly and can substantially increase flammability (Larson, 1980).

The live moss sampled in Tanacross on July 29 and July 30 was extremely dry in thinned and controls areas (mean moisture content of 2.2% and 2.3%) and potentially dangerous. The Tetlin – Tanacross data exhibit this trend throughout the majority of the season, signifying that the measurements taken in this study are temporally representative of site conditions. The Fine Fuels Moisture Code (FFMC) estimated by on site Remote Automated Weather Stations (RAWS) represented very high to extreme surface spread with FFMC vales of 91.6 to 95.6 from June 21st throughout the remaining sampling period, with the exception of one sampling date. (Alexander and Cole). (Refer to Appendix A for categorical summaries of predicted fire behavior by fuel code values.) Fine Fuels Moisture Code ratings reached 95 twice, coming extremely close to the maximum achievable value of 96 (De Groot, 1987). Fires occurring on such days could have disastrous effects exceeding the limits of human suppression efforts.

The measured Duff Moisture Code was significantly different between thinned and control areas of interior Alaska, corresponding to the significant difference in dead moss moisture content. The average thinned value is 66.0 (n = 13) compared to 52.8 in the unthinned. The onset of extreme fire behavior begins at a Duff Moisture Code value of 60, meaning that thinning elevated fire conditions from high to extreme (Alexander and Cole). Thinned areas would be more susceptible to lightning ignitions, raising the expected number of fires from approximately 2.0 to 2.5 fires per 5,000 square km (De Groot, 1987), and increasing the duration of smoldering compared to unmanaged black spruce stands (Lawson et al, 1997).

Remote Automated Weather Stations (RAWS) did not reflect the measured Duff Moisture Code (Figure 6a). The RAWS underestimated the Duff Moisture Code at values below 60, reporting that conditions were wetter than actually measured, and overestimated conditions when measured values exceeded 60. In this case, underestimating the Duff Moisture Code can have severe implications, reporting less intense fire behavior and leaving fire managers unprepared. The overestimated RAWS values are not as critical to fire management because extreme fire behavior is already expected when values exceed 60 but it is still not a true representation of the moisture characteristics.

There is no significant difference in the measured Drought Code between thinned and control sites. This is not unexpected because the overall moisture content did not significantly differ in the upper duff layer. It may be important to note that 6 out of the 13 dates sampled had values ranging from 400-765, which predict moderate to high fire behavior. Even though there are no significant differences between thinned and control values, the upper duff still strongly contributes to overall fire intensity by sustaining combustion and making mop-up and extinguishment efforts increasingly difficult (Alexander and Cole). The RAWS significantly overestimated the Drought Code values by an average of 70, reporting that conditions are drier than actually measured (Figure 6b).

Even though only two of the three fuel codes reflect significant differences between the open and closed canopy, the overall fire danger rating portrayed by the measured Fire Weather Index predicts a higher intensity burn in thinned areas. The average Fire Weather Index for thinned plots in 25 (n = 13) indicating extreme overall fire activity compared to a less severe but still high intensity value of 22 in control plots (Alexander and Cole). The RAWS also overestimated the Fire Weather Index in control and thinned areas but had the strongest relationship between measured and estimated values (r^2 = .93). Thinned black spruce stands have the potential to experience more severe fires with higher fire line intensities due to drier surface fuel layers.

Implications of Increased Fire Behavior

Alterations in surface fuel moisture due to thinning can have a profound impact on the effectiveness of shaded fuelbreaks. The purpose of this management technique is to reduce the rate of fire spread by changing the fuel arrangement (thinning) and to reduce surface flammability by promoting live understory with high foliar moisture content (Agee et al, 2000). The results of this experiment indicate the opposite effect in black spruce forests. Opening up the canopy exposes feathermoss to higher winds (contributing to higher rates of fire spread) and warmer ground temperatures, which create drier surface conditions. Feathermoss species do not thrive under these conditions and slowly die, creating more flammable fuels.

Shaded fuelbreaks are also used as a management tool to prevent surface fires from becoming crown fires. The initiation of crown fires is determined by the combination of fireline intensity (controlled by fuel moisture content) and height to tree crown (Van Wagner, 1977). The combination of the fuel codes and weather conditions measured in this experiment indicated higher potential intensities in thinned areas. Even though the thinned areas were also pruned, a higher intensity fire may still be able to ignite the black spruce crowns.

Conclusion

The results of this study show that live moss and dead moss fuel layers in thinned black spruce stands in interior Alaska have drier surface conditions. The live and dead moss layers provide the upper duff layer with enough protection to avoid accelerated drying conditions linking to thinning, yielding no significant changes in moisture content. The measured Fire Weather Index demonstrated a higher fire danger rating in thinned plots, therefore predicting increased fire severity and intensity. Thinned tree stands have different moisture dynamics that are not consistently illustrated by the current fire prediction models and could critically impact management decisions. Further investigations are needed to determine the effectiveness of thinning and the use of shaded fuelbreaks, but indicators suggest that this management technique may have undesired effects and promote higher intensity fires.

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Appendix A: Canadian Fire Weather Index

The Fire Weather Index is a numerical rating system used to determine the effects of weather on wildfires (De Groot, 1987). It is comprised of five elements that address fuel moisture and weather conditions. The three components that correspond to fuel moisture include: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC).

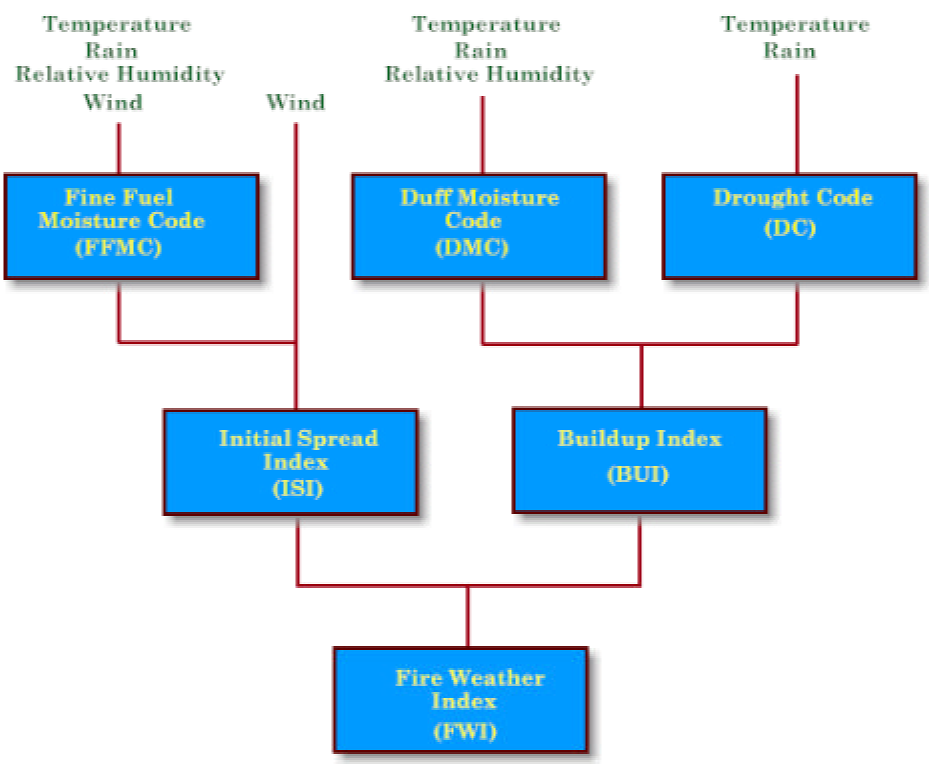
The FFMC represents the moisture content of surface litter and fine fuels (live moss) which are easily impacted by temperature, wind speed, relative humidity, and rain (at least 0.5 mm). The moisture content in the live moss only reflects weather conditions experiences in the previous 3 days because fast drying rates. The FFMC is used to predict the ease of fire ignition. Ignition is possible starting at FFMC values of 70, high potential is predicted at values ranging from 86-89, and 96 is highest probable value.

Duff Moisture Code (DMC) includes the moisture content of more loosely compacted and moderately decomposed organic layer (dead moss). The moisture content of dead moss is impacted by rain (at least 1.5 mm), temperature, and relative humidity. The dead moss layers have a time lag of 12 days. Combustion is attained at a DMC value of 20 and extreme behavior starts at 60.

Drought Code (DC) that serves as an indicator of moisture content in deeper more decomposed layers (upper duff) (1987). Temperature and rainfall of at least 2.8 mm impacts upper duff moisture content. Sub-surface fire is not expected with DC values below 300 and extreme behavior begins 500.

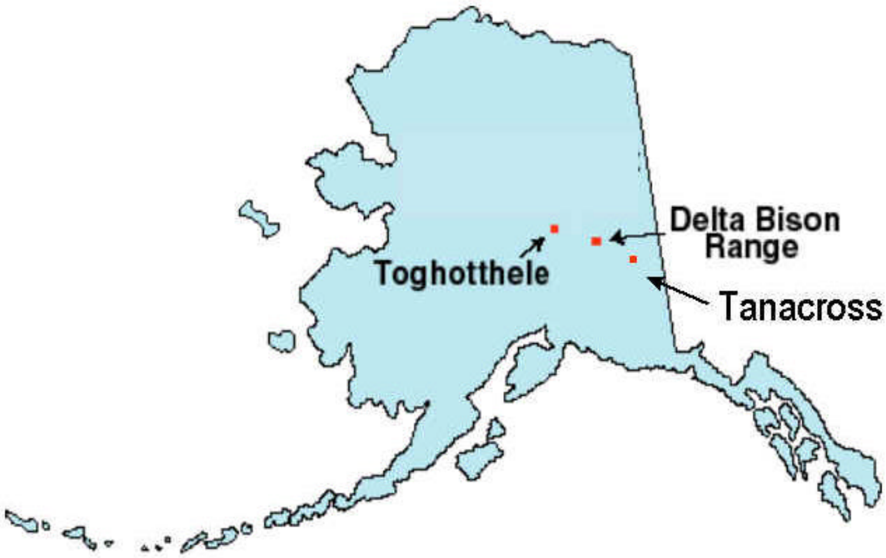
The Initial Spread Index (ISI) is a combination of the Fine Fuel Moisture Codes and wind speed (Stocks et al. 1989). The Build UP Index (BUI) is an expression of the amount of fuels available for combustion (Alexander and Cole, 1994).

The Fire Weather Index uses the previous days' precipitation and current weather information to predict the fire conditions at the hottest point of the day (1600 hrs) (De Groot, 1987). The Fire Weather Index can be used to estimate fire front intensity and aid in prevention and planning techniques (Stocks et al, 1989)



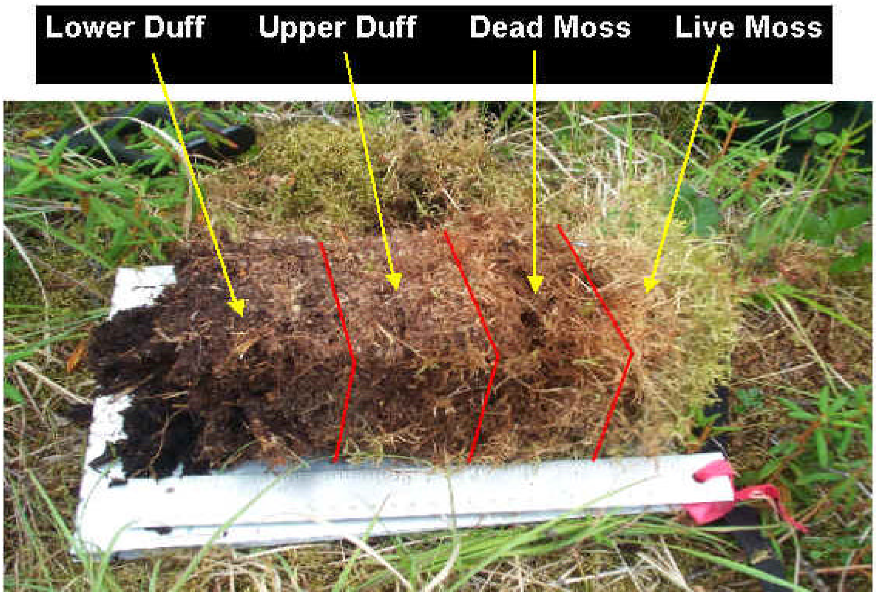
Components of the Fire Weather Index (Alaska Fire Service, 2004)

Appendix B. Site map



(Alaska Fire Service, 2004)

Appendix C: Photographs and Illustrations



C.1 Sample duff plug from Toghotthele site.

C.2 Browning patches of feathermoss and wind damage to black spruce trees in thinned Delta plot.

C.3 Green feathermoss carpet in Delta control plot.

C.4 Dry and dead moss in thinned Tanacross plot

Appendix D: Fuel Moisture Data

D.1 Raw percent volumetric moisture content

Site	Live Moss		Dead Moss		Upper Duff	
	Thinned	Control	Thinned	Control	Thinned	Control
Delta	6	8	8	12	10	10
	6	16	7	12	7	9
	8	14	10	18	22	20
	4	12	12	13	11	9
	3	15	7	14	13	13
	2	13	7	14	36	11
Mean	4.8	13.0	8.5	13.8	16.5	12.0
SE	0.8	1.1	0.8	0.8	4.0	1.6
Tanacross	2	3	3	5	6	9
	2	2	4	11	10	11
	2	2	3	1	7	11
	2	2	2	4	9	11
	4	3	5	3	6	11
	1	2	4	3	7	12
Mean	2.2	2.3	3.5	4.5	7.5	10.8
SE	0.4	0.2	0.4	1.4	0.6	0.4
Toghotthele	3	13	4	51	13	11
	2	10	3	43	10	35
	2	7	4	28	12	18
	10	19	27	50	33	33
	5	15	18	16	16	14
	7	16	5	16	17	21
Mean	4.8	13.3	10.2	34.0	16.8	22.0
SE	1.3	1.8	4.1	6.6	3.4	4.0

D.2 CFFDRS Calculated and Weather Stations comparison

FORMULAS USED: (to calculate the fuel moisture % predicted by CFFDRS using RAWS data)

DMC Formula

DMC White spruce, feather moss (Whitehorse, Yukon)

Eq1 $MC = \exp[(DMC - 149.6)/-20.9]$ $DMC = \{[\ln(MC)](-20.9)\} + 149.6$

DC Formula's

Lawson and Dalrymple 1996, White spruce duff (Whitehorse, Yukon)

Eq 2 $MC = 488.4/\exp(DC/267.9)$ $DC = [\ln(488.4/MC)] \times 267.9$

* Percent moisture content is gravimetric

** Data not availible

Site	Date	Live Moss %MC	Alaska Portable 4&5 RAWS FFMC	Dead Moss %MC	Alaska Portable 4&5 RAWS DMC	Meas DMC from DM %MC (EQ1)	Upper Duff %MC	Alaska Portable 4&5 RAWS DC	Meas DC from UD MC% w/EQ2	Lower Duff % MC
Tan-T	15-May-03	160.8	**	208.1	**	38.0	181.5	**	265.2	146.7
Tan-C	15-May-03	347.6	69.9	266.8	27.4	32.8	194.6	246.2	246.5	151.5
Tan-T	21-May-03	47.7	**	184.2	**	40.6	226.5	**	205.9	169.5
Tan-C	21-May-03	61.2	91.6	195.4	43.7	39.4	181.8	275.0	264.7	176.9
Tan-T	4-Jun-03	11.2	94.1	32.8	82.0	76.7	132.9	355.4	348.7	144.9
Tan-C	4-Jun-03	15.3	93.6	62.2	66.9	63.3	122.6	348.3	370.3	79.0
Tan-T	12-Jun-03	16.4	94.5	31.8	112.2	77.3	121.1	413.6	373.6	114.7
Tan-C	12-Jun-03	21.7	94.5	97.0	96.7	54.0	94.2	406.6	440.9	62.0
Tan-T	20-Jun-03	87.5	79.9	129.8	136.0	47.9	116.6	450.3	383.7	119.9
Tan-C	20-Jun-03	180.7	81.2	228.6	75.7	36.1	119.9	443.0	376.3	71.0
Tan-T	1-Jul-03	16.0	95.6	60.2	81.0	64.0	115.9	499.5	385.3	109.8
Tan-C	1-Jul-03	47.9	95.3	147.8	77.4	45.2	98.7	490.3	428.4	65.6
Tan-T	9-Jul-03	12.6	94.9	23.5	108.8	83.6	78.1	560.3	491.1	60.8
Tan-C	9-Jul-03	18.2	94.4	60.0	105.2	64.0	92.1	551.1	446.9	44.0
Tan-T	24-Jul-03	14.4	95.0	52.1	128.6	67.0	59.3	676.9	564.9	46.4
Tan-C	24-Jul-03	26.0	94.8	83.5	115.1	57.1	73.3	667.8	508.1	45.2

T = Thinned MC = Moisture Content DMC = Duff Moisture Code DC = Drought Code

C= Control FFMC = Fine Fuels Moisture Code DM = Dead Moss UD = Upper Duff

D.3 Fire Weather Index measured and estimated values for Tetlin - Tanacross samples

Site	Date	Estimated FFMC	WSM (km/hr)	ISI	BUI	FWI	Estimated FWI	Measured FWI
Tan-T	15-May-03	*	*	*	56	*	*	*
Tan-C	15-May-03	69.9	6.4	1	51	3	2.8	3
Tan-T	21-May-03	*	*	*	56	*	*	*
Tan-C	21-May-03	91.6	11.2	10	59	24	17	24
Tan-T	4-Jun-03	94.1	1.6	8	100	27	28.1	27
Tan-C	4-Jun-03	93.6	3.2	9	89	27	26.6	27
Tan-T	12-Jun-03	94.5	6.4	12	103	36	38.1	36
Tan-C	12-Jun-03	94.5	3.2	10	83	29	36.8	29
Tan-T	20-Jun-03	79.9	1.6	1.5	76	6	6.7	6
Tan-C	20-Jun-03	81.2	1.6	1.5	57	5	8.4	5
Tan-T	1-Jul-03	95.6	1.6	11	89	31	33.9	31
Tan-C	1-Jul-03	95.3	1.6	10	72	27	38.4	27
Tan-T	9-Jul-03	94.9	1.6	10	120	34	34.6	34
Tan-C	9-Jul-03	94.4	4.8	10	94	30	34.8	30
Tan-T	24-Jul-03	95.0	1.6	10	105	32	38.7	32
Tan-C	24-Jul-03	94.8	3.2	10	90	30	41.2	30

T =Thinned
C = Control

FFMC = Fine Fuels Moisture Code

* = no data

ISI = Initial Spread Index
WS = Wind Speed
BUI = Build Up Index
FWI = Fire Weather Index

D.4 Measured and RAWS estimated Fuel Codes

Site	Date Sampled	Measured DMC	Measured DC	RAWS Estimated FFMC	RAWS Estimated DMC	RAWS Estimated DC	WS km/hr	ISI	BUI	Measured FWI	Estimated FWI
Delta - T	7/29/03	61.8	417.5	86.7	52.2	495.9	6.9	4.0	92.0	16.0	13.1
Delta - C	7/29/03	51.6	503.0	86.7	52.2	495.9	2.7	3.0	85.0	12.0	13.1
Tanacross - T	7/29/03	88.2	611.5	92.1	145.5	713.8	1.6	6.0	133.0	25.0	31.5
Tanacross - C	7/29/03	79.7	667.2	91.7	131.4	704.4	1.6	6.0	122.0	24.0	26.9
Tanacross - T	7/30/03	76.2	538.7	92.4	149.5	721.4	3.2	7.0	114.0	26.0	32.7
Tanacross - C	7/30/03	88.2	514.3	92.0	135.2	711.8	4.8	7.0	126.0	27.0	31.1
Toghotthele - T	7/24/03	84.4	512.0	88.3	31.2	409.4	0.0	3.0	120.0	15.0	15.4
Toghotthele - C	7/24/03	33.5	349.2	88.3	29.1	402.1	0.0	3.0	52.0	9.0	12.0
Toghotthele - T	7/25/03	52.3	340.5	88.3	33.7	416.6	8.0	5.0	77.0	17.0	17.3
Toghotthele - C	7/25/03	41.9	333.3	88.3	33.7	416.6	8.0	5.0	64.0	15.0	17.3

T = Thinned
C = Control
DMC = Duff Moisture Code

DC = Drought Coded
FFMC = Fine Fuels Moisture Code
WS = Wind Speed

ISI = Initial Spread Index
BUI = Build Up Index
FWI = Fire Weather Index